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ROBUST AND COMPLEX ON-CHIP NANOPHOTONICS

Shanhui Fan
LELAND STANFORD JUNIOR UNIV CA

04/17/2015
Final Report

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14. ABSTRACT
The objective of this MURI is to achieve fundamental advances for understanding, designing, optimizing and applying complex non-periodic nanophotonic structures, with the aim of solving some of most important chip-scale photonics challenge including compact and robust components for wavelength division multiplexing, multi-spectral sensing, photovoltaics, optical switching and low-loss nano-scale localization of light.

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AFOSR-MURI 2009:
Robust and Complex On-Chip Nanophotonics

FINAL REPORT

I. Administrative Information

Grant Number:	FA9550-09-1-0704
Start Date:	30 September 2009
End Date:	31 March 2015
PI:	Shanhui Fan
	Phone: 1-650-724-4759. Email: shanhui@stanford.edu
Lead Institution:	Stanford University
Program Manager:	Dr. Gernot Pomrenke
	Phone: (703) 696-8426. Email: gernot.pomrenke@afosr.af.mil

II. Review Meetings

November 4, 2009, Boston Cambridge Marriott Hotel, Cambridge, MA. Our MURI program kicked off during part of a three-day AFOSR technical review.

December 1, 2011, Stanford, CA. This one-day technical review is attended by Dr. Gernot Pomrenke (AFOSR) and Dr. Jesse Mee (AFRL, Space Electronics Branch).

December 4, 2013, Harvard University, Cambridge, MA. This half-day technical review is attended by Dr. Gernot Pomrenke (AFOSR).

III. Program Objective

The objective of this MURI is to achieve fundamental advances for understanding, designing, optimizing and applying complex non-periodic nanophotonic structures, with the aim of solving some of most important chip-scale photonics challenge including compact and robust components for wavelength division multiplexing, multi-spectral sensing, photovoltaics, optical switching and low-loss nano-scale localization of light.

IV. Scientific Approach

In nanophotonics, extensive research has been carried out on photonic crystals and meta-materials, leveraging the conceptual analogy to solid-state physics. However, there is in fact no intrinsic reason to prefer such regular periodic structures. Modern lithographic techniques can create nano-scale patterns with near-arbitrary structural complexity. Moreover, in each of application challenges as outlined above, it is almost certain that rationally designed non-periodic structures will far outperform periodic ones, due to the enormous number of degrees of freedom non-periodic structures possess.

Our team is developing the capability to understand, exploit and manage such enormous numbers of degrees of freedom in complex nanophotonic structures, by a combined computational,

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theoretical and experimental approaches. In the computational efforts, we develop advanced nanophotonics simulation capabilities that achieve orders-of-magnitude speed-up compared with conventional methods, as well as optimization techniques based upon inverse design and optimization techniques aiming to achieve performance robustness. The theoretical efforts are leading to new insights in understanding the fundamental theoretical limits of performance of nanophotonic devices. The computational and theoretical efforts are closely coupled to experimental efforts on various dielectric and metallic on-chip nanophotonic structures, leading to novel devices in ultra-compact wavelength splitters, and nano-lasers and modulators with very low energy consumption.

V. Team Members

Our team includes 7 PI's from Stanford, MIT and Cornell:

Stanford:	Shanhui Fan (PI)
	Stephen Boyd
	Mark Brongersma
	Jelena Vuckovic
	David A. B. Miller
MIT:	Steven G. Johnson
Cornell:	Michal Lipson

Total Number of Contributing Ph. D. Students: ~25

Total Number of Contributing Research Associates and Visiting Scientists: 5

VI. Financial Execution

We provide here the financial execution of our MURI project for every budget period up to now:

Period 1
Dates: 9/30/09 – 6/30/10
Duration: 9 months
Budget: $ 891,667 (866,667 plus supplement of $25,000)
Expense: $ 226,553

Period 2
Dates: 7/01/10 – 1/31/11
Duration: 7 months
Budget: $ 600,000
Expense: $ 700,519

Period 3
Dates: 2/01/11 – 1/31/12
Duration: 12 months
Budget: $ 1,100,000
Expense: $ 1,178,572

Period 4

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Dates: 2/01/12 – 9/30/12
Duration: 8 months
Budget: $ 733,333
Expense: $ 940,215

Period 5
Dates: 10/01/12 – 4/30/13
Duration: 7 months
Budget: $ 366,666
Expense: $ 596,310

Period 6
Dates: 5/01/12 – 4/30/14
Duration: 12 months
Budget: $ 1,100,000
Expense: $ 938,856

Period 7
Dates: 5/01/14 – 9/30/14
Duration: 5 months
Budget: $ 733,334
Expense: $ 578,763

Period 8 – No Cost Extension
Dates: 09/30/14 – 03/31/15
Duration: 6 months
Budget: $ 0
Expense: $277,256

TOTAL BUDGET: $5,525,000
TOTAL EXP: $5,525,000

We under-spent in the first period. This was due, in part, to an unexpected delay in subcontract negotiation between Stanford and MIT, which in the end took approximately one year to resolve. In response to this under-spending, in Periods 2-5 we have been spending at a rate that is higher than initially budgeted. In Period 6 and 7 we again under-spent, in particular, due to late arrival of the funds from the AFOSR to us, sometimes by a few months, which significantly delayed the financial execution at the two subcontractors at Cornell and MIT. As a result, we have requested, and was granted, a no-cost extension for six months. All funds were spent at the end of the no-cost extension period.

VII. Major Accomplishments to Date

Our MURI team efforts are organized along three thrusts:

Thrust 1: Advances in Simulations, Optimizations and Theory
Thrust 2: Application Drivers and Experimentations

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Thrust 3: Integration and Control

We have made substantial progresses along each of the thrusts. In Thrust 1, the team has invented computational algorithms that result in several orders of magnitudes speed up for the simulation of nanophotonic structures. The team has also developed new optimization strategies that enable more efficient and robust design of nanophotonic structures, and new theoretical insights in the properties of aperiodic structures in general. In Thrust 2, the team has combined the computational and optimization efforts as described in Thrust 1, with experimental and characterization efforts, to achieve new devices and capabilities in on-chip nanophotonics. In particular, the team has developed ultra-compact wavelength splitters in both dielectric and plasmonic structures, and robust coupler between optical fiber and on-chip waveguide based on a novel transformation-optics approach. Finally, in Thrust 3, the team has made substantial progresses in integration and control of on-chip complex photonic structures. The highlight in this thrust includes an experimental realization of a non-magnetic on-chip silicon isolator based on a novel interband dynamic photonic transition concept, the demonstrations of on-chip electrically-pumped nano-lasers with record-low threshold pumping current, and on-chip nano-modulators with ultra-low energy consumption below 1fJ/bit, and the proposal and demonstration of photonic gauge potential and gauge field based on dynamic modulation.

Below we provide more in-depth discussion on our scientific accomplishments:

Thrust 1: Advances in Simulations, Optimizations and Theory

- One of our MURI-team's goals is the realization of ultra-compact wavelength splitters for on-chip WDM, focal plane arrays, and new solar cells designs. **Brongersma** has developed a rapid optimization technique for aperiodic plasmonic grating structures to achieve the above-mentioned functions in a single patterned layer of metal. He first investigated the scattering properties of free space photons and surface plasmons with individual grooves of different width and depth. He then used the knowledge of the scattering properties of the individual grooves to very efficiently simulate the behavior of a multi-groove structure using a transfer-matrix (TM) type model.
- **Boyd** has developed a new method for handling bi-convex problems, which include many photonics design problems. The standard approach is to alternate between minimization over one group of variables (typically a field) and another (typically the structure). The new method is based on the alternating directions method of multipliers (ADMM), and adds proximal regularization to the alternating minimizations. ADMM gives an improvement in robustness, and sometimes convergence rate, when compared to the standard method of alternating minimization. But far more interesting is that fact that ADMM leads naturally to algorithms that are distributed, and so can be implements on various multiple processor platforms, such as GPGPUs, clusters, or a cloud. **Boyd** has implemented a single processor version of the method for simple and small problems; his next goal is to scale this up to much larger problems, and from there to multi-processor implementation.
- **Fan** and **Miller** have developed a computational technique, based on the Dichrelet-to-Neumann (DtN) mapping method, that allows about three-order of magnitude improvement of simulation speed as compared to conventional finite-difference time-domain (FDTD) or finite-difference frequency-domain (FDFD) methods for two-dimensional on-chip complex photonic crystal circuit structures. The DtN method also results in a two order-of-magnitude

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reduction in the dimension of the system matrix. As a result, the inverse of the system matrix becomes computable. Knowing the inverse of the system matrix, once the solution for one structure is obtained, the solution of the Maxwell's equations for a slightly varied structure can be obtained with far less computational cost. Such a capability enables evaluation of large numbers of structures in a relatively short period of time, which is essential for large-scale optimization of nanophotonic structures. Related to this work, **Fan** has further shown that the DtN method enables fast density-of-state calculations, which is useful for design aperiodic structures for enhancing performances of solar cells and thermal radiation detectors.

- Finite-difference frequency-domain (FDFD) method is a very important technique for plasmonic device simulation, since the method directly incorporates the frequency dispersion of metal dielectric function, and can be easily parallelized for large-scale numerical simulations. However, in practice the method is plagued by inconsistent convergence behaviors due to the fact that the system matrix resulting from the discretization of the Maxwell's equation is poorly conditioned. The **Fan** group has discovered that the condition number of the system matrix, and hence the convergence behavior of the algorithm, can be drastically improved with the use of the correct kind of Perfectly-Matched-Layer (PML) boundary condition. His efforts may enable the FDFD method to be widely adopted for nanophotonic simulations.

- The **Fan** group has made publically available a nanophotonic simulation software package based on the Rigorous Coupled Wave Analysis (RCWA) method. This package is particularly useful for complex grating simulations.

- **Johnson** has developed new optimization-based approach for designing multimode transformation-optics devices while incorporating manufacturability constraints (bounded indices and minimal anisotropy) in collaboration with the **Lipson** group. **Johnson** has demonstrated results (optimized designs and simulations) for "mode squeezer" and multimode bend devices, with orders of magnitude lower inter-modal scattering than are achieved in straightforward manual designs. A key development was the identification of a practical way to incorporate critical design constraints (the end-facet index profiles and locations) implicitly into the basis. In a related result, **Johnson**'s understanding of the mathematical foundations of transformation optics led to new rigorous bounds on the difficulty of "invisibility cloaking," and in particular he showed how cloaking (even on a ground plane) becomes necessarily more difficult (in terms of manufacturing constraints) in proportion to the diameter of the cloaked object.

- **Johnson**, in collaboration with the Kimerling group at MIT, has investigated optimization-based design of complex textures for thin-film photovoltaic cells. He showed that the complex and counter-intuitive texture design could achieve optimal angle-sensitivity/absorption tradeoffs (exceeding Lambertian limits over a limited range of angles) in a thin-film geometry. Such an optimal trade-off previously could only be achieved with bulky solar-concentrator approaches.

- **Johnson** has developed a local-density of states (LDOS) approach to inverse design of microphotonic devices, including full solution of the Maxwell equations and full calculation of three dimensional problems and true radiative losses. The initial application was to microcavity design, where he demonstrated the ability to generate complex aperiodic

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structures (e.g. image below) from ab-initio optimization of the LDOS at a single point, computed by FDFD simulations. A key mathematical development was the ability to compute a frequency-averaged LDOS by analytic continuation to a single complex-frequency problem, allowing one to impose practical bandwidth requirements extremely efficiently. Another important result was the identification of successive refinement of the optimized bandwidth as a way to accelerate convergence and escape local optima; the resulting designs proved nearly insensitive to the starting guess (vacuum, random structures, photonic crystals), despite the probable non-convexity of the problem. Johnson also demonstrated full 3d results computed on a workstation with a high enough resolution to see the basic topology of the cavity emerging, while higher-resolution designs seem feasible on supercomputers (or with the new iterative solver techniques developed in the **Fan** group).

- **Johnson** and **Boyd** extended their earlier work on robust optimization in photonics to the design of ultra-compact couplers between waveguides with large impedance mismatches—converting ordinary waveguides into "slow" waveguides where the group velocity is greatly reduced (for efficiently enhancing light-matter interactions). By optimizing the coupler as a function of coupler size, they showed that optimization can achieve an ideal exponential tradeoff between length and loss, and results in increasingly non-obvious taper shapes as the slowness of the waveguide becomes more extreme. By formulating the optimization problem with built-in awareness of manufacturing uncertainties, they showed that the resulting design is dramatically more robust than straightforward loss minimization, and is even robust to errors in the modeling—allowing them to use a simplified ultrafast computational scheme.

- **Miller** has extended previous works on fundamental limits of nanophotonic structures to 3D optical systems, including non-periodic ones and ones of arbitrary complexity, for applications including optical splitters.

- **Miller** has a preliminary proof of a new design method that apparently can tell us the required refractive index distribution to make an arbitrary linear optical component, at least for paraxial optical systems. Importantly, this method is non-iterative and based only on linear algebra. The design is obtained by the inversion of a specific matrix. Such a design method is apparently unknown in the literature – other approaches to such arbitrary design are typically iterative and/or non-linear mathematical approaches. If this method holds up under practical conditions, it could lead to substantial reductions in the calculations for design of aperiodic optical systems, eliminating the need for iterative or optimization algorithms at least for some problems.

- **Vuckovic** has previously developed an inverse design algorithm for nanophotonic devices, which relies on complementary convex optimization, and alternates between the steps of optimizing structure and field. Using this algorithm, she was able to design a variety of nano-resonators in 2D, and the optimization time was less than 10 minutes on a PC. **Vuckovic** and **Boyd** have subsequently extended this method to design 3D resonators in planar geometries by employing the 2.5D approximation, i.e., by considering planar 3D structures as sections of "photonic crystal fibers".

- **Vuckovic** has developed an "objective-first" design method, which places more weight on satisfying the design objective (such as maximum coupling efficiency) than satisfying physics during the optimization process. Using this approach, she was able to design a variety of efficient couplers between different types of waveguides in 2D (dielectric

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waveguides, plasmonic MIM waveguides, plasmonic wires, and photonic crystal fibers). The coupling efficiencies in all of the studied couplers were ~95% and design time ~10 minutes per coupler. All couplers had footprint smaller than $4\lambda^2$, where λ is the operating wavelength.

- The **Vuckovic** group has successfully extended the object first design method to 3D by leveraging an efficient FDFD electromagnetic solver algorithm developed by the **Fan** group. The FDFD solver was implemented on graphics processing units (GPUs), enabling the fast optimization of 3D devices. In addition, her group developed a structure binarization step,so that the optimization leads to manufacturable structures. Using the objective first design method, her group designed a wide variety of efficient, compact, and manufacturable waveguide-based devices, including mode converters, mode multiplexers, waveguide crossings, grating couplers, and broadband WDM devices. The inverse design process is relatively fast: for a typical device with a footprint of 4 x 4 um, the entire optimization process takes approximately 10 hours on a single server with 3 GPUs. Finally, her group has experimentally demonstrated an inverse designed grating coupler which combines WDM and vertical coupling functions, although this particular structure was designed in 2D rather than 3D.

Thrust 2: Application Drivers and Experimentations

- Spectral imaging and sensing techniques, new solar cell designs and wavelength-division multiplexing in optical communication rely on structures that collect and sort photons by wavelength. The strong push for chip-scale integration of such optical components has necessitated ultra-compact, planar structures, and fomented great interest in identifying the smallest possible devices. Meanwhile, the optical coupling of subwavelength plasmonic structures supporting a very limited number of modes has also enabled new functionalities, including Fano resonances and structural electromagnetically-induced transparency. The **Brongersma** group has shown that two similarly sized subwavelength metal grooves can form an ultracompact submicron plasmonic dichroic splitter. Each groove supports just two electromagnetic modes of opposite symmetry that allows independent control of how a groove collects free-space photons and directs surface plasmon polaritons. These results show how the symmetry of electromagnetic modes can be exploited to build compact optical components.

- **Fan** and **Miller** have successfully designed a ultra-compact wavelength splitter for Dense Wavelength Division Multiplexing (DWDM) applications, by combining the DtN numerical method as discussed above, with simulated annealing approach for device optimization. Near-ideal performance for a three-channel splitter is reached after an optimization process that involves the evaluation of over 60,000 structures. (See Fig. 1)

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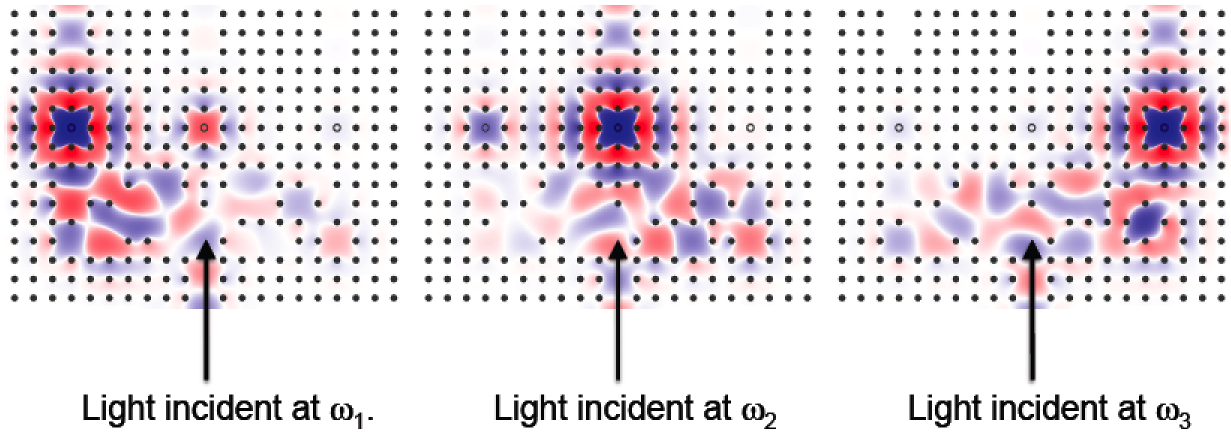

Fig. 1. A design of a compact aperiodic WDM filter structure. Shown here are the steady state field distributions of three frequencies being separated out into three different output waveguides.

- **Fan** has shown that non-periodic photonic crystal heterostructures have thermal conductance that decays exponentially as the length of the conductance channel, and hence have thermal conductance that is several orders of magnitude below vacuum. Thus he has predicted that on-chip thermal insulators based aperiodic structures can far outperform conventional thermal insulator structures.

- **Johnson** consider the problem of optimized gradient-index structures via transformational optics — designing focusers, magnifiers, and other structures such as bends that have unique multimode properties: transporting and distorting light while preserving the relative phases and amplitudes of all modes. A key difficulty of transformational optics is that an arbitrary transformation generates difficult-to-manufacture materials with strange anisotropies and unattainable index contrasts. **Johnson** overcomes this by applying nonlinearly constrained optimization to maximally focus/expand light in a minimal volume while maintaining isotropy and attainable materials, compatible with a new fabrication technology in the **Lipson** group. In this way, he can preserve the unique light-transport properties of transformational optics, exploiting the efficiency of a semi-analytical design that avoids the need for repeated wave simulations, while avoiding the associated fabrication drawbacks.

- Non-periodic nanophotonic devices are capable of performing beyond their standard counterparts, often displaying impressive novel features. Their structures commonly rely on smooth variations of refractive index across the device, especially when designed via Transformation Optics, and this gradient is fundamental for their performance. **Lipson** has developed a low-loss fabrication platform for gradient-index silicon devices, including devices designed via transformation optics. She produced 3-dimensional thickness profiles on the guiding layer of devices using Focused Ion Beam (FIB) milling. This process can be easily and precisely controlled, leading to surface roughness on the order of just 2 nm. Her techniques outperform other methods, such as gray-scale e-beam lithography and photo-lithography, commonly used for micro-electro-mechanical devices, which are not as well behaved at the nano-scale since they result in significantly rougher structures. Based on this platform, **Lipson** integrated a gradient-index lens with conventional inverse tapers and, due to the aberration-free imaging characteristic of this lens, she was able to reduce the alignment

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sensitivity in the fiber-to-waveguide coupling system, gaining, for example, 6 dB at 4 µm misalignment.

- **Miller** has successfully fabricated and tested two-conductor plasmonic slot mode waveguides integrated with photodetectors. These have shown propagation lengths of ~ 9 microns in guides with modes and metal line separations of ~ 80 nm, operating with Au metals and at ~ 850 nm wavelength. Importantly, this propagation length agrees with simulations, which means that, though the surface properties of metals might in practice be different from their bulk properties and surface roughness might conceivably affect mode propagation, in fact the devices do work as simulated. They have also in the past year been able to route light round bends in such waveguides. Hence, they have shown that optical circuits, operating at deeply subwavelength scales, can likely be fabricated and exploited in ways very similar to coplanar waveguide circuits in the RF or microwave domains.
- **Miller** and **Brongersma** have designed, fabricated and demonstrated a novel plasmonic wavelength splitter integrated with a photodetector. In this device, slits are fabricated in a thin metal sheet on top of a dielectric substrate. When light shines on the surface of the sheet, the interaction of the light with the slits leads to surface plasmons being generated that propagate along the surfaces of the metal. They employed a design algorithm in which, starting from a regular array of slits in the metal, they slightly displace the slits in a blind optimization algorithm to achieve their desired design, which was to put one wavelength at one output point, a second at another, and so on. They fabricated and tested this designed device, successfully separating three wavelengths to three different detector positions, thus effectively making an integrated wavelength demultiplexer. Importantly, this device is not performing the same function as a grating or prism – it is not smoothly scanning the output wavelength, but is instead putting ranges of input wavelength at each desired output point. We therefore have much greater design flexibility in the function of the device than is typically available in conventional optical components.

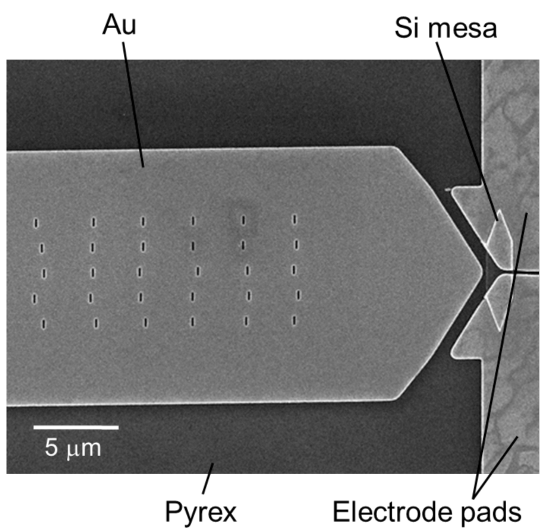

Fig. 2. Top view of a plasmonic wavelength demultiplexer integrated with a photodetector. Shining light on the top of the structure leads to plasmons propagating along the metal surface. The deliberately slightly non-periodic arrangement of the slits leads to separation of wavelengths at different vertical positions at the right of the structure where photodetectors can be placed. One photodetector is shown in this picture also.

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- **Miller** has made a series of major advances in basics of design of arbitrary optical components. He started by showing a clear, universal way to describe linear optical devices mathematically, based on singular value decomposition. This shows that all linear optical components can be described as mode converters, and, conversely, if we can make an arbitrary mode converter, we can therefore make an arbitrary optical component. Using this approach, he then quantified a lower bound on how complicated an optical component has to be, a bound that is met by several different recent designs. Then, he showed that there is at least one way of making any such linear optical component. This particular approach is completely progressive and non-iterative. This approach, based on a mesh of interferometers aligned one after the other, is a possible practical method of making arbitrary optical components of moderate complexity, using for example silicon photonics. Furthermore, by showing constructively how to make any linear optical component, this approach constitutes the first proof that any linear optical component that is otherwise physically legal can be designed. Extensions of the work (completed primarily under other funding) offer ways of making completely self-aligning optical components (See Fig. DM1), of automatically finding the best orthogonal coupled channels through any linear optical system, and of implementing spatial add-drop multiplexers. This work was highlighted as one of the major developments in photonics in 2013.

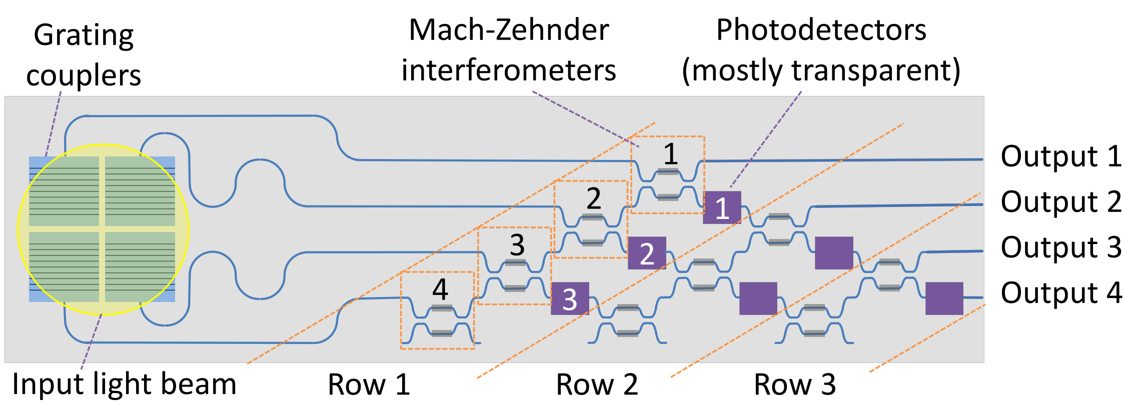

Fig. 3. Optical structure capable for achieving any linear optical operation.

- **Brongersma** created a unidirectional plasmon launcher by creating an array of aperiodically arranged grooves carved into a metallic film. The structure takes light from free space and converts it into SPPs propagating in a specific direction. Although certain aperiodic unidirectional launchers have been demonstrated in the past, their inherent asymmetrical nature suggested that optimization techniques capable of traversing the large parameter space of multiple aperiodic grooves can lead to more optimal designs. In some ways, it is the simplest groove structure that benefits from numerical optimization, making it a good base case to investigate. Unidirectional launching of SPPs has attracted a body of research in the past several years with a recent finding of an 11-groove structure that provides a nearly 50-to-1 ratio in the launched power from normally incident light. This structure made use of grooves of varying depth and its fabrication was very challenging. Other unidirectional launchers have been designed but required either light of a particular oblique angle of incidence, patterned two-dimensional arrays, or more complicated fabrication such as slanted

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grooves. Brongersma realized a design that uses simple, rectangular grooves of uniform depth as building blocks. With an optimized design, they experimentally demonstrated unidirectional launching with a launching ratio of over 50 using only 5 grooves.

- **Brongersma** realized a compact wavelength division demultiplexing device that consist of 5 gooves and 3 slits carved into a metal film. The structures takes normally incident light on one side of the metal, effectively splits in into signals centering around three different wavelengths, and these signal emerges out of the slits on the opposing side of the metal. This is a basic structure that allows for integrated color pixel detectors on a chip.

Thrust 3: Integration and Control

- **Lipson** and **Fan** have developed of a fully CMOS compatible integrated optical isolator based on the engineering of inter-band photonic transitions in a waveguide which are controlled with a dynamic electric modulation of the index of refraction.
- **Vuckovic** has developed an efficient method to electrically control optical nanocavities in planar geometry, by implementing lateral p-i-n junctions (Fig. 3). Such junctions are defined by lithography and ion implantation, which enables efficient integration of passive and active devices on a chip. Using this approach, **Vuckovic** has demonstrated the lowest threshold electrically injected photonic crystal nanocavity laser, with ~180nA lasing threshold, and single mode photonic crystal LED that is directly modulated at 10Gb/s at room temperature, with energy consumption below 1fJ/bit. These works were featured in numerous media outlets, including San Francisco Chronicle, Wired, and Laser Focus World.

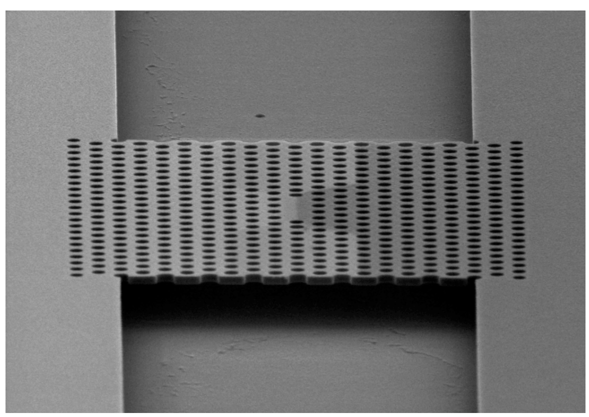

Fig. 4: Lateral p-i-n junction formed by ion implantation in QD active GaAs material

- **Fan** has discovered that in photonic structures undergoing temporal refractive index modulation, the phase of the modulation can provide a gauge potential for photon. By engineering the spatial distribution of such phases, one can achieve a photonic Aharonov-Bohm (AB) interferometer that functions as an optical isolator, and create an effective magnetic field for photons that are capable of achieving a photonic analogue of quantum Hall effect without the use of any actual magnetic field. **Fan** has provided an initial demonstration of the photonic AB effect in the radio-wave frequency range, and in collaboration with **Eggleton** of University of Sydney, provided a demonstration AB effect using discrete optical component in fiber in the visible wavelength range. **Lipson** and **Fan** has realized the

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photonic AB effect on a silicon chip, where a silicon non-magnetic isolator is achieved using only two modulators.

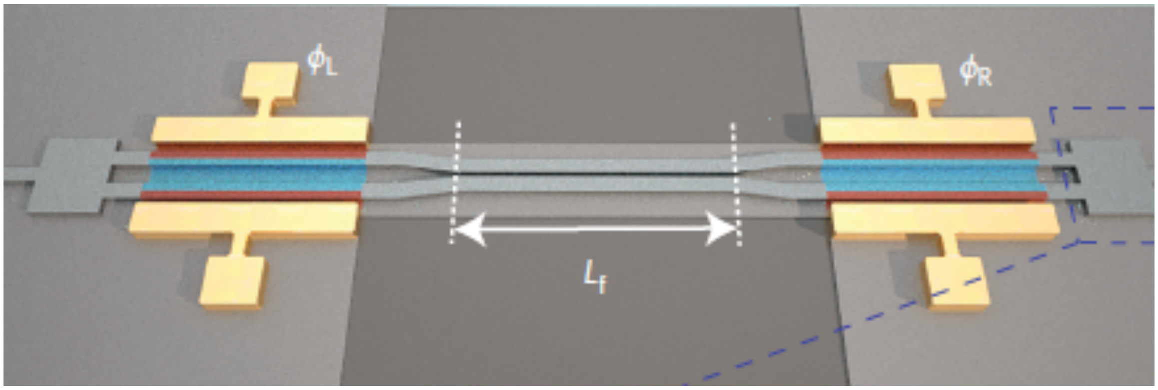

Fig. 5: An integrated photonic AB interformeter on a silicon chip.

VIII. Publications

2010

1. J. Lu and J. Vuckovic, "Inverse design of nanophotonic structures using complementary convex optimization", Optics Express 18, 3793-3804 (2010).

2. W. Lau, J. T. Shen and S. Fan, "Exponential suppression of thermal conductance using coherent transport and heterostructures", Physical Review B 82, 113105 (2010).

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3. J. Lu, S. Boyd and J. Vuckovic, "Inverse design of a three-dimensional nanophotonic resonator", Optics Express 19, 10563 (2011).

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6. V. Liu, Y. Jiao, D. A. B. Miller, and S. Fan, "Design methodology for compact photonic-crystal-based wavelength division multiplexers", Optics Letters 36, 591-593 (2011).

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8. X. Sheng, S. G. Johnson, J. Michel, and L. C. Kimerling, "Optimization-based design of surface textures for thin-film Si solar cells", Optics Express 19, A841-A850 (2011).

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9. T. Tanemura, K. C. Balram, D. –S. Ly-Gagnon, P. Wahl, J. S. White, M. L. Brongersma, and D. A. B. Miller, "Multiple-Wavelength Focusing of Surface Plasmons with a Nonperiodic Nanoslit Coupler", Nano Letters 11, 2693-2698 (2011).

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73. A. A. Asatryan, L. C. Botten, K. Fang, S. Fan, and R. C. Mcphedran, "Two dimensional Green's tensor for gyrotropic clusters composed of circular cylinders", Journal of the Optical Society of America A, vol. 31, pp. 2294-2303 (2014).
74. Alexander Y. Piggott, Jesse Lu, Thomas M. Babinec, Konstantinos G. Lagoudakis, Jan Petykiewicz, and Jelena Vučković, "Inverse design and implementation of a wavelength demultiplexing grating coupler," Scientific Reports 4, 7210 (2014).

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75. M. T. H. Reid, J. K. White, and S. G. Johnson, “Generalized Taylor–Duffy method for efficient evaluation of Galerkin integrals in boundary-element method computations,” IEEE Transactions on Antennas and Propagation, vol. 63, pp. 195–209, (2014).

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76. L. Yuan and S. Fan, “Dynamic localization of light from a time-dependent gauge field for photons”, under review in Physical Review Letters.
77. Y. Shi, Z. Yu and S. Fan, “Dynamic reciprocity in nonlinear optical isolators”, accepted in Nature Photonics.
78. Alexander Y. Piggott, Jesse Lu, Konstantinos G. Lagoudakis, Jan Petykiewicz, Thomas M. Babinec, and Jelena Vuckovic, “Inverse design and demonstration of a robust, ultra-compact, and broadband on-chip wavelength demultiplexer, accepted in Nature Photonics (2015).
79. X. Huang and M. Brongersma, "Color splitting of light scattered via aperiodic plasmonic groove arrays”, to be submitted to Physical Review B.

IX. Honors and Awards Since 2009

Brongersma: Global Climate and Energy Project Distinguished Lecturer (2013)
Promoted to full Professor (2012)
SPIE Fellow (Elected 2011)
APS Fellow (Elected 2010)
The Raymond and Beverly Sackler Prize in the Physical Sciences (2010)
Keck Faculty Scholar, Stanford University (2008-2011)

Boyd: Member of the National Academy of Engineering (Elected 2014)
IEEE Control Systems Award (2013)
Mathematical Optimization Society Beale-Orchard-Hays Award (2012)
UC Berkeley Outstanding E.E. Alumnus Award (2011)

Fan: Appointed Director of the Edward L. Ginzton Laboratory (2014).
Promoted to full Professor (2012)
Global Climate and Energy Project Distinguished Lecturer (2011)
IEEE Fellow (Elected 2010)
SPIE Fellow (Elected 2009)

Johnson: Promoted to Associate Professor with Tenure (2011)

Lipson: Promoted to Givens Foundation Professor (2013)
IEEE Fellow (Elected 2013)
The MacArthur “Genius” Award (2010)
Blavatnik Award, NY State Academy of Science (2010)

Miller: Member of the National Academy of Engineering (Elected 2010)

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Member of the National Academy of Sciences (Elected 2009)

Vuckovic: Promoted to full Professor (2013)
Hans Fischer Senior Fellowship (2013)
Marko V. Jaric Award (2012)
The Humboldt Research Award (2010)

X. Transition planning

The MURI team has maintained interactions and collaborations with scientists in the Department of Defense and in Industry:

The **Brongersma** group is actively discussing their current research on non-periodic device structures with researchers at Northrop Grumman, who are interested in this research for imaging applications.

Fan has visited AFRL during the summer of 2011 and presented seminars on the MURI work. **Fan** has also initiated a STTR project from AFRL (FA8650-12-C-1472, Program Manger: Peter Marasco), which builds upon the results of this MURI as well as a previous MURI on plasmonics.

The **Johnson** group is interacting with Dr. DeLacy from U.S. Army Edgewood Chemical Biological Center, with regard to the MURI research on the obscurance applications of maximizing cross-section.

Fan has recently started interaction with Beausoleil's group at HP labs in using adjoint variable methods for photonic device optimization.

XI. Issues of Concerns

None.

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1.

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Organization / Institution name

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Grant/Contract Title

The full title of the funded effort.

Robust and Complex On-Chip Nanophotonics

Grant/Contract Number

AFOSR assigned control number. It must begin with "FA9550" or "F49620" or "FA2386".

FA9550-09-1-0704

Principal Investigator Name

The full name of the principal investigator on the grant or contract.

Shanhui Fan

Program Manager

The AFOSR Program Manager currently assigned to the award

Gernot Pomrenke

Reporting Period Start Date

09/30/2009

Reporting Period End Date

03/31/2015

Abstract

The objective of this MURI is to achieve fundamental advances for understanding, designing, optimizing and applying complex non-periodic nanophotonic structures, with the aim of solving some of most important chip-scale photonics challenge including compact and robust components for wavelength division multiplexing, multi-spectral sensing, photovoltaics, optical switching and low-loss nano-scale localization of light.

In nanophotonics, extensive research has been carried out on photonic crystals and meta-materials, leveraging the conceptual analogy to solid-state physics. However, there is in fact no intrinsic reason to prefer such regular periodic structures. Modern lithographic techniques can create nano-scale patterns with near-arbitrary structural complexity. Moreover, in each of application challenges as outlined above, it is almost certain that rationally designed non-periodic structures will far outperform periodic ones, due to the enormous number of degrees of freedom non-periodic structures possess. Our team is developing the capability to understand, exploit and manage such enormous numbers of degrees of freedom in complex nanophotonic structures, by a combined

computational, theoretical and experimental approaches. In the computational efforts, we develop advanced nanophotonics simulation capabilities that achieve orders-of-magnitude speed-up compared with conventional methods, as well as optimization techniques based upon inverse design and optimization techniques aiming to achieve performance robustness. The theoretical efforts are leading to new insights in understanding the fundamental theoretical limits of performance of nanophotonic devices. The computational and theoretical efforts are closely coupled to experimental efforts on various dielectric and metallic on-chip nanophotonic structures, leading to novel devices in ultra-compact wavelength splitters, and nano-lasers and modulators with very low energy consumption.

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Archival Publications (published) during reporting period:

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1. J. Lu and J. Vuckovic, “Inverse design of nanophotonic structures using complementary convex optimization”, Optics Express 18, 3793-3804 (2010).
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Changes in research objectives (if any):

None

Change in AFOSR Program Manager, if any:

None

Extensions granted or milestones slipped, if any:

A no-cost extension of six months was granted, due to late arrival of the funds from the AFOSR to us, sometimes by a few months, which significantly delayed the financial execution at the two subcontractors at Cornell and MIT.

AFOSR LRIR Number

LRIR Title

Reporting Period

Laboratory Task Manager

Program Officer

Research Objectives

Technical Summary

Funding Summary by Cost Category (by FY, $K)

	Starting FY	FY+1	FY+2
Salary			
Equipment/Facilities			
Supplies			
Total			

Report Document

Report Document - Text Analysis

Report Document - Text Analysis

Appendix Documents

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